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DISLOCATION KINETICS BEHIND SHEAR SHOCKS*

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ABSTRACT

High velocity oblique impact experiments result in both compression and shear shock waves. Behind the shear shock wave the particle velocity is transverse to the shock front. At large transverse particle velocities, dislocation kinetics can contribute a portion of the velocity. Based on a kinematic and thermodynamic model of dislocation kinetics, an analysis is made of the transverse strain and velocity behind a shear shock. Kinematics of dislocations in transverse motion behind the shock is formulated. A solution is given for an ideal case where the dislocation density function propagates as a pulse behind the shear shock.

INTRODUCTION

Oblique impact experiments have been performed to investigate metallic material response at high shear rates[1-4]. The inclined impact experiment results in both a compression shock wave and transverse or shear shock wave that propagate through the test specimen. The compression waves propagate faster than the transverse wave. The high shear rates occur across and behind the transverse wave. The particle velocity across a transverse shock wave has a discontinuity in the vector component perpendicular to the propagation direction of the shock front. For an elastic shock, the discontinuity in the transverse particle velocity results in a propagating discontinuity in the shear strain and in the shear stress; and the deformation after the shock is recoverable. For strong shocks which involve dislocations the deformation after the shock is not all recoverable. The following analysis considers the simplest case of dislocation kinetics across and behind a transverse shock. The field equations and the discontinuity conditions across a shock front for mass, momentum, and energy depend on a dislocation density function. In addition, there is a field equation and a discontinuity condition across a shock front for the dislocation density function. These equations and their associated discontinuity conditions are described elsewhere.[5-7]

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DISLOCATION DEPENDENT SHEAR SHOCK ANALYSIS

For a planar shear shock, coordinate axes can be selected such that the shock front propagates along the X_2 axis with velocity $\underline{V} = (0,V_2,0)$ and the particle velocity behind the shock front is along the X_3 axis. In the simplest idealized case, the nonrecoverable plastic deformations can occur from edge dislocations. For a statistical dislocation species distribution that depends only on the velocity of dislocations, the edge dislocation would have a fixed Burgers' vector $\underline{b} = (0,0,b_3)$, a velocity vector variable relative to the lattice structure $\underline{\nu} = (0,0,\nu_3)$, and a fixed line tangent vector $\underline{\xi} = (-\xi_1,0,0)$. The field equation and the discontinuity condition across a shock front[7] for the dislcocation density function $D(\underline{x},t,\underline{b},\underline{\nu},\underline{\xi})$ are given by

$$\dot{D} = \partial_t D + \underline{\nabla}\cdot((\underline{v} + \underline{\nu})D) = P + K\ \{\underline{\nu} \leftrightarrow \underline{\nu}^*) \tag{1}$$

and

$$[(\underline{V} - \underline{v} - \underline{\nu})D]\cdot\underline{n} = p + k\ \{\underline{\nu} \leftrightarrow \underline{\nu}^*\} \tag{2}$$

Equation (1) is a field equation of the Boltzmann type for the dislocation density function at spatial points without shock fronts, equation (2) is the discontinuity condition across a shock front propagating at velocity $\underline{V}$, and the other functions are for the mass velocity $\underline{v}$, the unit normal to the shock front $\underline{n}$, the volume production for dislocation species $(\underline{b},\nu,\underline{\xi})$ denoted by P, the shock surface production for dislocation species $(\underline{b},\underline{\nu},\underline{\xi})$ denoted by p, and K and k are the transition functionals for modelling dislocation interchanges between different velocities for species $(\underline{b},\nu,\underline{\xi})$ and $(\underline{b},\nu^*,\underline{\xi})$ in the volume and at a shock surface, respectively. For a simple illustration, K and k are taken as zero and only a model for the production of dislocations is considered. A uniform density pulse of edge dislocation species (b_3,ν_3,ξ_1) that propagates at velocity V_2 can be represented with a step function as

$$D(\underline{x},t,b_3,\nu_3,\xi_1) = D_o(H(V_2t - x_2) - H(V_2t - x_2 - X_2)) \tag{3}$$

where the pulse width is X_2, D_o is a constant, and H is the step function which is unity when the argument is positive and zero otherwise. Equation (3) satisfies equation (1) at points away from the shock front and satisfies equation (2) at the "elastic-dislocation" shock front for $x_2 = V_2t$ and at the dislocation shock front for $x_2 = V_2t - X_2$. The production function creates dislocations at a rate of D_oV_2 at the elastic-dislocation shock front and annihilates dislocations at a rate of $-D_oV_2$ at the dislocation shock front.

From previous concepts developed for the deformation and kinematics due to dislocation kinetics,[5-7] the total relative particle velocity at points χ behind a shock front currently located at $\underline{x}$ is given by

$$v_i\}(\underline{x}\to\underline{\chi},t) = v_i|(\underline{x}\to\underline{\chi},t) + \int_{\underline{x}}^{\chi}\int_Q b_i e_{jk\ell}\xi_k\nu_\ell D + b_i e_{jk\ell}\xi_k b_\ell^*\dot{D}\,d\underline{q}\,dx_j(\underline{x}\to\underline{\chi},t) \tag{4}$$

For the transverse shock and edge dislocation species discussed above, index $i = 3$, index $j=2$, index $k = 1$, and index $\ell = 3$, this identifies the permutation tensor component $e_{213} = -1$. The total transverse particle velocity $v_3\}$ behind the shock has a lattice structure velocity term $v_3|$ and an edge dislocation velocity component represented by the integration over the dislocation species $\underline{q}(\nu)$ in domain Q and the integration over the spatial points in domain $(\underline{x} \to \underline{\chi})$. In previous work[5-7] the dislocation dependent contribution to the total relative velocity is denoted by $v_i]$ where "]" is used to identify the accumulated discontinuities from dislocation flux and dislocation density rate changes represented by the integrand. The parameter $\underline{b}^*$ in the integrand is the displacement that occurs when dislocation density changes occur, for example when new dislocations are created or when dislocations undergo transitions from $\underline{\nu}^* = 0$ to $\underline{\nu}^* = \underline{\nu}$.

For this simple illustration of deformation across and behind a transverse shock involving a propagating pulse of edge dislocations, equations (2), (3) and (4) imply that the relative transverse particle velocity can be integrated for $(x_2 - X_2) \leq \chi_2 \leq x_2$ to give

$$v_3\}(x_2 \to \chi_2, t) = v_3|(x_2 \to \chi_2, t) - b_3 e_{213} \xi_1 \nu_3 (\chi_2 - x_2) D_0$$

$$- b_3 e_{213} \xi_1 b_3^* V_2 D_0 \Big|_{x_2} \tag{5}$$

In equation (5) the discontinuities that contribute to the particle velocity from the dislocation flux term, $\nu_3 D_0$, behind the shock is represented as spatially linear by using a mathematical approximation that smooths the peaks in dislocation density that occur between atomic planes, and the contribution to the particle velocity from dislocation density changes at the shock front located at x_2 contains the term $b_3^* V_2 D_0$. The other contribution to particle velocity is the lattice structure term $v_3|$; which would have a discontinuity at the shock front in order for the shear strain, and consequently, shear stress discontinuities to occur.

As discussed in the previous thermodynamic analysis for dislocation kinetics the amount of work performed by the shear stress must be greater than the local thermodynamic chemical potential for dislocation kinetics[5-7] to occur at and behind the shock front. This thermodynamic chemical potential concept replaces the continuum plasticity concepts of a stress dependent yield condition that has numerous different forms in phenomenological approaches.

In order to illustrate some kinematic and thermodynamic aspects of dislocation kinetics for shear shocks, consider a shock impact that inputs a sustained and constant transverse particle velocity $v_3\}_0$ that propagates through a material which is initially at rest and stress free. Thus, the particle velocity $v_3\}_0$ must be attained from the lattice structure velocity $v_3|$ and the dislocation dependent velocity $v_3]$ of equation (5) evaluated at $\chi_2 = x_2 - X_2$, which is the end of the dislocation pulse. As discussed earlier, at the point, $x_2 - X_2$, a dislocation shock occurs to terminate the dislocation pulse; therefore, the relative velocity expression across the shock plus the dislocation pulse becomes

$$v_3\}_o = v_3\}(x_2 \rightarrow x_2 - X_2, t) = v_3|(x_2 \rightarrow x_2 - X_2,\ t) - b_3 e_{213}\xi_1 \nu_3 X_2 D_o$$

$$- b_3 e_{213}\xi_1 b_3^* V_2 D_o|_{x_2} + b_3 e_{213}\xi_1 b_3^* V_2 D_o|_{x_2 - X_2} \qquad (6)$$

For purposes of illustration, it is assumed that the lattice structure velocity $v_3|$ has a discontinuity at the shock front and is then constant behind the shock front so that the recoverable shear strain and the associate shear stress are also uniform in the domain $(x_2 \rightarrow x_2 - X_2)$ of the dislocation pulse. Then neglecting the contributions to particle velocity from the dislocation density changes at x_2 and $x_2 - X_2$, equation (6) represents a linear increase in transverse particle velocity behind the shock due to the propagating pulse of edge dislocations behind the shock front. Thus, the shearing gradient of the nonrecoverable transverse velocity term from this dislocation pulse is constant and is given by

$$\Delta_2 v_3\} = - b_3 e_{213}\xi_1 \nu_3 D_o \qquad (7)$$

which is the "plastic strain rate" in dislocation theory.[8,9]

Finally, the nonrecoverable relative displacement from the dislocation flux term, $\nu_3 D_o$, over the pulse width can be obtained by a time integration; and for uniform shock propagation velocity V_2 it is a quadratic function of the pulse width, given by

$$u_3](x_2 \rightarrow x_2 - X_2, t) = - b_3 e_{213}\xi_1 \nu_3 D_o X_2^2 / 2V_2 \qquad (8)$$

The rate energy is dissipated by the dislocation flux term is the nonrecoverable work rate per unit volume performed by the shear stress[5,6] and is given by

$$\Delta\dot{\bar{W}}\Big|_{\text{dislocation flux}} = - \sigma_{32} b_3 e_{213}\xi_1 \nu_3 D_o \qquad (9)$$

where the shear stress for small strain elasticity is

$$\sigma_{32} = G\ v_3|/V_2 \qquad (10)$$

Here, G is the elastic shear modulus and $v_3|/V_2$ is the recoverable or elastic strain across the shock front. Then the nonrecoverable work rate for the dislocation pulse volume behind the shock front is given by

$$\Delta\dot{\bar{W}}\Big|_{\text{dislocation flux}} = - \sigma_{32} b_3 e_{213}\xi_1 \nu_3 D_o X_2 \qquad (11)$$

From the thermodynamics of dislocation kinetics,[5-7] this part of the work rate is converted to entropy production; and would result primarily in a localized temperature increase behind the shock front. For narrow dislocation pulse widths and high dislocation flux densities, a rapid temperature increase would occur and would dissipate the energy of a transverse shock front. Thus, for liquids containing dense sets of dislocations,[6] the propagation of shear shocks over long distances is not possible.

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